Acousto-Ultrasonic In Situ Monitoring of Fatigue Cracking in an Aircraft Wing Skin Specimen

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ABSTRACT

The concept of in situ Structural Health Monitoring (iSHM) involves incorporating a diagnostic capability to detect and monitor damage in structural ‘hot spots’. These systems allow the introduction of Condition Based Monitoring (CBM) approaches for ageing aircraft fleets and thus could help significantly reduce through-life support costs and increase aircraft availability. The Australian Defence Science and Technology Organisation (DSTO) has a program of work aimed at developing autonomous, robust, reliable iSHM systems with the specific aim of retro-fitment to existing aircraft. A current laboratory demonstrator of the technology is focused on the application of an acousto-ultrasonic (AU)-based iSHM system for monitoring fatigue cracks on generic structurally-detailed lower wing skin (LWS) panel specimens. This particular scenario, which simulates the LWS on an F-111C aircraft, is considered an ideal developmental platform and springboard for future iSHM applications, since it captures a number of key issues that AU-based iSHM systems need to address to ensure robust reliable diagnostics, viz., complex structural geometry, crack closure and high operational loads. This paper describes the design, application and assessment of an AU-based iSHM system to detect and monitor growth of fatigue cracking in the generic complex-geometry LWS panel specimens subject to representative spectrum loading. Its performance is discussed and compared to measurements furnished by thermoelastic stress analysis and visual observation. Testing associated with this complex realistic panel specimen revealed several deficiencies in the design of the iSHM system.

INTRODUCTION

A significant through-life support cost driver for military aircraft is time-based non-destructive inspections for structural defects. When an inaccessible region of an aircraft is involved, such inspections can be particularly costly and time-consuming. The

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introduction of Condition Based Maintenance (CBM) approaches using in situ Structural Health Monitoring (iSHM) systems has the potential to reduce costs and increase aircraft availability. iSHM facilitates the early detection (and possibly characterisation) of defects in high value Australian Defence Force (ADF) assets thus providing a critical underpinning technology for efforts to improve the efficiency of contemporary structural integrity management practice. The Australian Defence Science and Technology Organisation (DSTO) has a program of work aimed at developing autonomous, robust, reliable iSHM systems with the specific aim of retro-fitment to existing aircraft. One technique, under investigation by DSTO, uses acousto-ultrasonics (AU). That approach offers an effective broad area, low sensor density, low-cost and reliable means of non-destructive inspection. This technique is based on the propagation of elastic waves from a fixed source, typically using piezoelectric materials, which are sensed at a separate receiving location where variations from the baseline response are used to identify damage within the wave path.

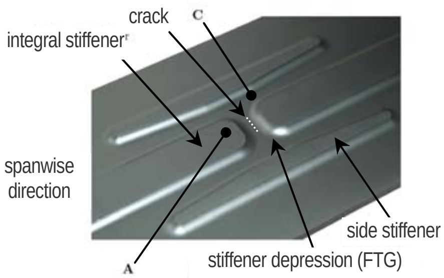
Activities at DSTO are focused on a laboratory demonstration of the feasibility of AU-based iSHM systems on realistic aircraft components, the development of an AU modelling capability, the assessment of robustness of piezoelectric ceramic (piezoceramic) transducers and strategies for ensuring system robustness [1, 2, 3]. This paper describes the design, application and assessment of an AU-based iSHM system for monitoring fatigue cracks on generic complex-geometry lower wing skin (LWS) panel specimens subject to representative spectrum loading. This particular scenario considers the lower wing skin (LWS) of an F-111C aircraft at the Forward Auxiliary Spar Station FASS281.28, where an integral fuel transfer groove (FTG) is a known site for fatigue cracking. The application is considered an ideal developmental platform and springboard for future iSHM applications, since it captures a number of key issues that AU-based iSHM systems need to address to ensure robust reliable diagnostics, including complex geometry, crack closure and high operational loads.

SPECIMEN DESIGN

Figure 1 illustrates the FTG geometry on the inside of the F-111 LWS at the FASS 281.28 location. A more detailed description of the region can be found in references [1], [4] and [5]. In essence, the FTG produces a local loss in span-wise stiffness which leads to out-of-plane bending, adding to the tensile stress in this region. As a result, cracks initiate on the inside surface of the wing skin, and tend to propagate chordwise along the FTG for some distance before penetrating the wing skin. It is an awkward problem for NDI, in part because the crack only fully penetrates the skin after growing a considerable length in the chordwise direction, but also because of crack closure. The closure stems from a combination of the loading of the wing when the aircraft is at rest on the ground, and from residual compressive stresses established by tensile plastic deformation in the FTG. A considerable effort was made by DSTO and the RAAF to develop eddy current procedures to reliably detect cracks under these conditions.

The generic complex-geometry lower wing skin (LWS) panel specimen, based on the FTG at FASS281.28 problem, is shown in Figure 1. It is believed the panel specimen contains several key characteristics that are vital for the development of an effective iSHM capability, viz.:

- Complex geometry. The panel consists of a series of integral stiffeners, with bolted structure, which influence significantly the propagation of stress waves, and hence



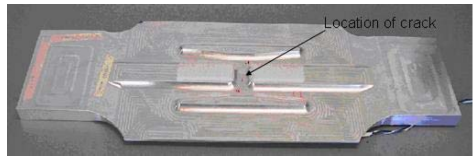


Figure 1. Internal view of F-111 LWS around the FTG (left). Generic structurally detailed LWS panel specimen designed around the F-111 LWS FTG region (right).

require robust strategies to mitigate any effect this may have on crack detection methodologies. A validated modeling capability would be extremely beneficial, if not essential, in understanding the AU response in such complicated structural scenarios, thus enabling the determination of optimal transducer design and placement as well as acoustic mode selection.

- Transducer durability. The FTG location experiences flight spectrum loading with strain excursions exceeding 3000 $\mu\varepsilon$. Consequently, the application requires a robust transducer as well as a good understanding of transducer performance under high mechanical loading and a methodology to assess transducer condition.
- Complex cracking scenario. Cracking initiates from the side opposite to the transducer attachment location and has been observed to include significant crack closure that may obscure detection of the crack and generally complicate the interpretation of the AU response.

These panel specimens also allow the investigation of the ‘active smart patch’ (ASP) concept [1], i.e. composite bonded patches that incorporate an integrated AU system. The composite bonded patch is applied either as a reinforcement to stop crack initiation or as a repair to reduce crack growth. The function of the AU system within the ASP is to (i) furnish information on the structural integrity of the bondline - the key issue for certification of composite bonded repairs (CBR), and (ii) monitor crack growth in the parent structure. In this case additional issues are the performance of the AU system with embedded and/or surface mounted transducers, validating embedment techniques and assessing the impact of embedment on the structural integrity of the bonded patch. It is believed that the demonstration of an iSHM system on a realistic scenario such as this, rather than on a simplified plate type specimen, will contribute more to achieving confidence and acceptance of the technology by fleet maintainers.

SYSTEM DESIGN

Positioning the piezoelectric elements optimally is a key element in the design framework, since these transducers are permanently attached. Optimality can involve a variety of factors, but in this study it primarily targets the sensitivity of the system to structural damage in the host, in this case cracking in the FTG. Another important consideration is the need to avoid exposing the transducers to high operational strains, which in the present application means that the FTG is excluded as a potential transducer location. Also minimising variations in system output due to deviations in transducer placement, say during installation, or the location and geometry of the crack is another issue to ensure optimal system robustness.

Maximum damage detection sensitivity is generally achieved by placing transducers in locations where the scattering of structural plate waves from a defect is strongest. Ideally the AU response of this structure would be numerically modelled using FE techniques in order to determine the best sensor locations, as it allows an almost limitless flexibility in the potential transducer layout configurations, drive frequencies, and damage modes/locations that can be considered. However, during the initial stages of this program FE modelling performed on the FTG structure did not have the fidelity required to provide a useful predictive capability for the purpose of design. One of the contributing reasons was the simplified (and customary) approach taken to model the piezoceramic actuator transduction, viz. a point force or piston mode of excitation. More recent modelling has shown some excellent correlation between FE and experiment when more realistic excitation schemes are used [6]. For the purpose of this program however an empirical approach was taken whereby the elastic wave field in the FTG region was surveyed using laser vibrometry (LV). It was impractical to consider a large number of possible actuator positions in this empirical approach. Hence an engineering judgement was made to identify two candidate actuator positions, viz. positions A and C shown in Figure 1. Initial LV surveys of the coupon revealed that position C produced the vastly stronger acoustic wave field within the FTG, thus all subsequent surveys were performed using only this source location.

The test coupon was scanned in two structural states: (i) pristine and (ii) damaged. The pristine or baseline state was considered first with scans performed for acoustic drive frequencies of 300, 406, 750, 1100 and 1250 kHz. In each case the drive signal applied to the piezoceramic transducer comprised a 5 cycle Hanning modulated tone-burst. With the baseline response established, the specimen had a notch machined into the FTG to simulate a crack. This notch was semi-elliptical in profile, approximately 10 mm long, 1 mm wide and 1.8 mm deep. The specimen was carefully realigned and the scans repeated. Figure 2 shows some representative scan results. Two points are worth noting. A distortion or refraction of the wave-field through the stiffener, caused by a change in plate thickness in this region and consequently a change in the phase velocity for Lamb waves, is evident in all images. The effect of the notch on the wave-field is noticeable, with the perturbation strongest in the wake of the notch and the crack trailing edge acting like a secondary source. Intuitively it would be expected that the intensity

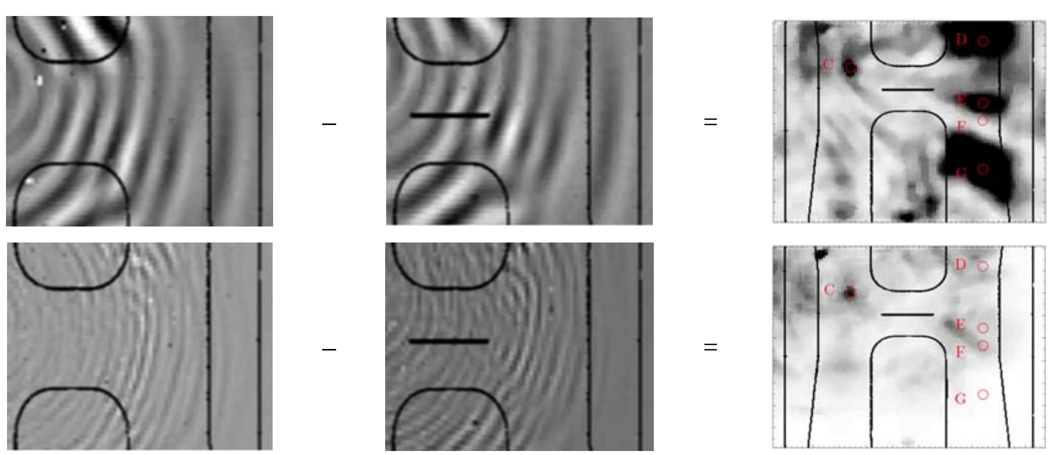


Figure 2: Out-of-plane velocity fields, as measured by the laser vibrometer, in the FTG region, for no damage (left), with a 10 mm long and 1.8 mm deep notch (centre) and the resultant scatter intensity (right) at an excitation frequency of 300 kHz (top) and 1100 kHz (bottom).

and spatial location of the perturbation would depend on the location of the crack trailing edge with respect to the source. The effect is more easily discerned from a map of the scattered field (see Figure 2), which is derived by subtracting the incident wave field measured for the baseline case from the wave-field measured for the notched case [3]. Note the scattered fields were calculated from the main wave front and excluded reflected waves from the specimen boundaries. The darker regions in the scattered field correspond to regions of relatively high scattering from the crack. Based on the results for these two excitation frequencies, four candidate sensor locations, D, E, F and G, were selected.

EXPERIMENTAL SET-UP

Four panels were prepared, P-01 to P-04, but only panels P-01-P-03 will be reported here. Crack initiation and growth in the FTG region was achieved through the application of a loading regime representative of an F-111 flight spectrum, with peak tensile and compressive stress of up to 241 and 60 MPa, respectively, and a mean stress of 53 MPa. The experimental set-up is shown in Figure 3. The piezoceramic transducers were subjected to peak tensile strains between 2600 to 3400 $\mu\varepsilon$. A thermoelastic stress analysis (TSA) system was employed to periodically inspect for crack initiation and growth within the panel. The thermoelastic (TE) inspections were undertaken, using the in-house developed MiTE (Microbolometer Thermoelasticity) system, during the testing program by periodically suspending the loading spectrum and applying a constant amplitude peak-to-peak tensile dominated stress of 60 MPa at a frequency of 10 Hz (Figure 3). AU measurements were taken after suspending the spectrum loading at regular intervals of 25 or 50 simulated flight hours (SFH), using the in-house developed AUSAM (Acousto-Ultrasonic Structural health monitoring Array Module) [5] to apply the excitation signal (with drive frequencies ranging from 300 to 1200 kHz) to the actuator located at C and to sample the response of piezoceramic sensors at D to G. For a given interrogation frequency the AU response at the sensor locations consists of several incident and reflected wave packets, as shown in Figure 3. During the test, the peak amplitude of pre-selected incident wave packets were tracked and measured using a Hilbert transform. The first wave packet is an inductively coupled artefact and was ignored in the analysis by appropriate time windowing.

RESULTS AND DISCUSSION

AU and TE measurements were taken on panel P-01 at regular intervals of 50 and 250 SFH, respectively. The variation in peak amplitude with increasing SFH for all sensors was monitored, but only results for the highest ranked sensor locations are presented in Figure 4. A sharp drop in peak amplitude for some modes for both interrogation frequencies of 1100 and 750 kHz was observed at around 1600 SFH,which implied the presence of a crack which was subsequently verified at 1750 SFH by the TE scan. For P-02 only sensors at locations E and F were monitored, and results for sensor F at 1100 and 1250 kHz are reproduced in Figure 4. A step change in all modes for both frequencies is observed at about 2500 SFH, where TE scans verified the existence of the crack. The sharp drop in signal amplitude associated with the presence of the crack is accompanied by a more gradual background reduction in signal that is thought to correspond to degradation of the piezoceramic elements or bondline. Should this reduction in response be severe enough there is a potential for this to mask the response due to the crack. With the issue of amplitude drift in mind, panel P-03 was tested to attempt to accentuate the AU response due to the crack, i.e. increase the sensitivity of the system to the crack. Crack closure is a known feature of the FTG problem and occurs due to residual compressive stresses established by tensile plastic deformation

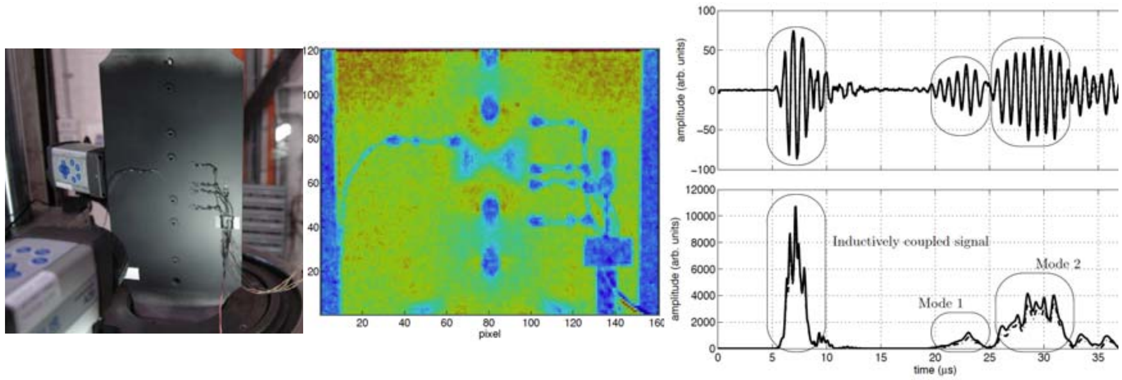


Figure 3: Experimental set-up (left), typical TE scan (centre) and, typical AU time history response of a piezoceramic sensor (top right) and resulting Hilbert transfer (bottom right).

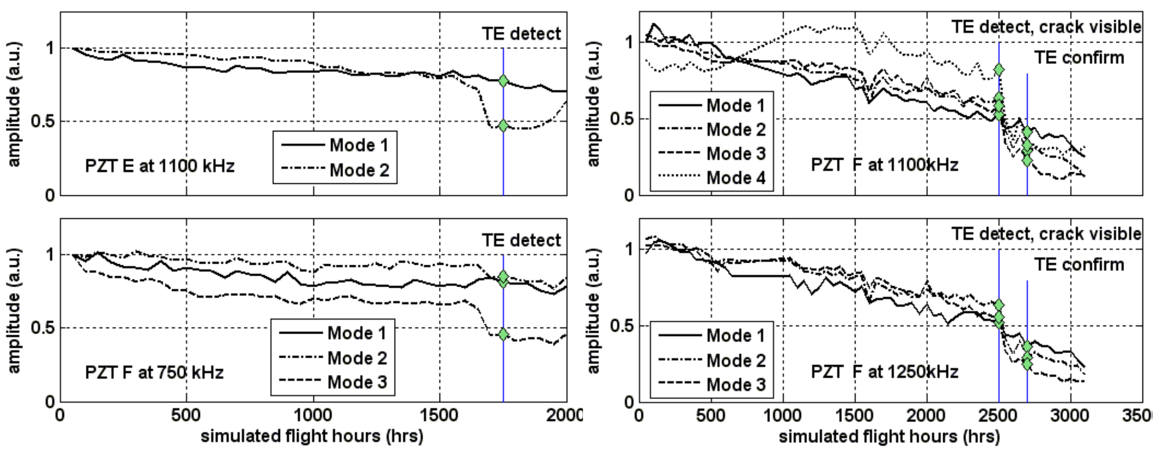


Figure 4: Variation in peak amplitude of AU response with increasing SFH for P-01 (left) and P-02 (right).

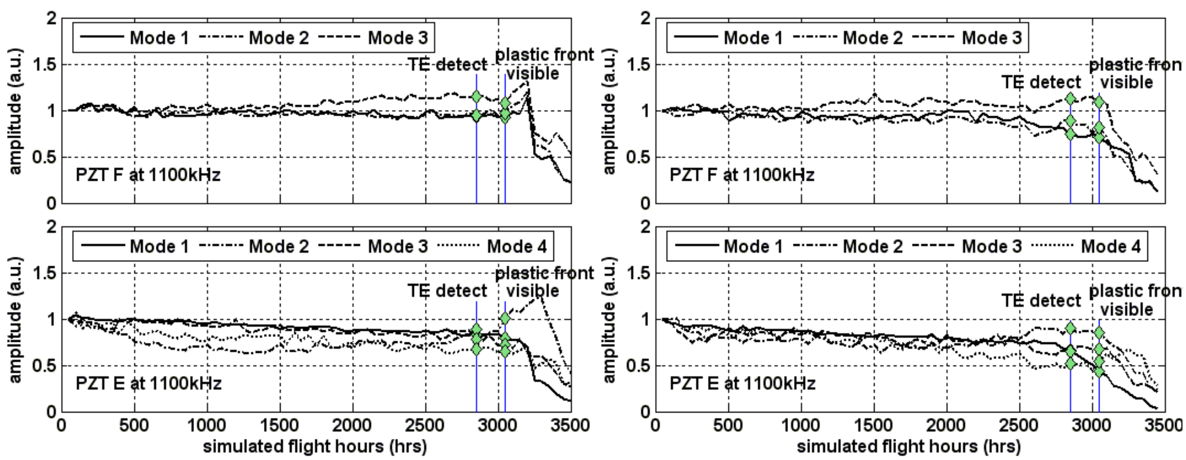


Figure 5: Variation in peak amplitude of the AU response for P-03 for the zero (left) and 60 MPa (right) static load condition.

around the crack tip. Previous AU and conventional ultrasonic studies have shown that closure significantly reduces the ultrasonic response of the crack [7, 8], however that response can be improved by introducing a tensile stress during inspection. A static tensile stress of 60 MPa was applied to the sample during AU interrogation in an attempt to counter the effect of closure. Figure 5 shows the variation in peak amplitude of the AU response with increasing SFH under 0 and 60 MPa static loading. Amplitude drift did not appear as severe for this panel as for the other two panels. A noticeable reduction in AU peak amplitude occurred only after 3200 SFH, which was well after the crack was detected by TE and visual inspection, i.e. at approximately 2800 to 3000 SFH. An inspection of the crack after the fatigue test revealed that it had grown under the actuator before detection by AU, a disappointing result. Also, applying a tensile load during interrogation did not appear to improve the detection sensitivity. Examination of the fracture surface showed relatively large amounts of aluminium oxide compared to the amounts found in P-01 and P-02, and relatively fewer "beach" or "shore" marks from the constant amplitude cycling applied during the TE scans. These indicators suggest a larger amount of fretting of the crack surface for P-03 which would be caused by larger contact stresses across the crack face, consistent with strong closure. Another possible factor is the alignment or orientation of the crack with respect to the FTG geometry, which previous studies [4] have shown can vary between nominally identical samples. A variation in that orientation was not accounted for in the design of the iSHM system and could compromise the detection sensitivity.

This highlights the limited nature of the empirical iSHM design process, which could not factor in all conceivable variables in the problem. Indeed, the sensor and actuator positions were chosen on the basis of just a limited empirical study that considered only one idealized representation of a crack i.e. a machined notch of a single profile, length, position and orientation. Also, the design process considered only a few discrete candidate sensor locations, interrogation frequencies and Lamb wave modes.

The results of this study emphasise the need for a validated modeling capability to facilitate a more systematic and efficient design process that considers a wider range of variables. Such a capability should allow a designer to determine element locations, system interrogation frequencies and modes that will achieve a more robust damage detection capability able to accommodate variations in the damage profile, location, direction and degree of closure. It should be noted that in conventional ultrasonic NDI the practitioner has the advantage of being able to adjust the position of the ultrasonic probe to account for damage variability, especially variations in location and orientation. In the case of iSHM no adjustment in position is possible since elements are structurally integrated, so additional work is required upfront in system design to account for this variability. It is of course possible to increase the size of the sensor array to achieve some flexibility with regards to transducer location but this has the disadvantage of increasing system complexity, although it offers other benefits such as increased redundancy and might assist in system self-diagnostics.

The systematic reduction in AU response with increasing spectrum loading was of particular concern. Although piezoceramic transducers have a high efficiency in the production and reception of AU waves, they have questionable durability under sustained mechanical loading at even moderate levels (greater then 2000 $\mu\varepsilon$) in the context of aircraft related structural integrity problems. Mechanical loading can cause degradation in a number of ways including stress depoling, disbonding within the transducer package or between the transducer system and the host. DSTO is undertaking a systematic durability testing program to understand piezoceramic performance under mechanical loading to understand the various damage modes and to develop and validate techniques to detect transducer degradation [9].

CONCLUSIONS

This study has applied an AU-based iSHM system to detect cracking in a laboratory panel specimen representing a real aircraft lower wing skin section. The complex structural geometry, realistic damage growth, and high mechanical loading associated with this application make it an ideal developmental test bed for any proposed iSHM system. In this study the testing program showed a number of deficiencies in the design framework and approach used in the first iteration of AU-based iSHM system described here. These deficiencies include, (1) the unavailability of a validated modeling capability to allow for robust system design, (2) performance degradation of the piezoceramic elements, (3) a limited system self-diagnostic capability and (4) limited system redundancy. Current DSTO research programs with the Cooperative Research Centre for Advance Composite Structures (CRC-ACS), the DSTO Centre of Expertise in Structural Mechanics (CoE-SM) and the USAF Air Force Research Laboratory (AFRL) aim to address these issues.

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